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The work reported herein was sponsored by the U. S. Army Transportation Research Command, Fort Eustis, Virginia, in an effort to explain further the electrostatic charging of helicopters.

This command concurs in the conclusions and recommendations made herein.

The development of an electrostatic discharger for helicopters is presently being pursued by this command. Reports on this effort will be distributed upon completion.

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Task 1D121401A 14130

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Contract DA 44-177-TC-844

TRECOM Technical Report 64-14

June 1964

MEASUREMENT PROGRAM TO DETERMINE STATIC ELECTRICITY CHARGING CURRENTS IN HELICOPTER MAIN ROTOR BLADES

Prepared by:

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Stratford, Connecticut

for

U. S. ARMY TRANSPORTATION RESEARCH COMMAND
FORT EUSTIS, VIRGINIA

PREFACE

This report was prepared by Sikorsky Aircraft, a division of United Aircraft Corporation, under the United States Army Contract Number DA 44-177-TC-844. The measurement program was originated by an unsolicited proposal to the U.S. Army Transportation Research Command at Fort Eustis, Virginia. Mr. S. Blair Poteate was the Army Project Engineer and Mr. Samuel Baron was the Sikorsky Aircraft Project Engineer, assisted by Mr. Edward Cholakian and Mr. Thomas M. Coonan.

The project was conducted during the period from June 1962 to August 1963.

The author wishes to acknowledge the excellent cooperation, comments, and suggestions of Mr. S. Blair Poteate.

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SUMMARY

Most interested parties have generally accepted the theory that the main rotor blades of helicopters are the chief contributors to the electrostatic charge on helicopters. This program was designed to measure the main rotor blade charging current and to compare this current with the total helicopter current. This was accomplished by electrically insulating a main rotor blade from its rotor head on a test stand and measuring the charging current, and by similarly insulating a main rotor on a hovering helicopter and measuring the blade current and total helicopter current. Tests were performed using a 2000-horsepower rotor test stand, a 1500-horsepower blade balance stand, and a SH-3A turbine-powered aircraft.

A 2000-horsepower main rotor test stand was used to whirl a CH-34 insulated main rotor blade for a period of time commencing in October 1962 and terminating in April 1963. The total test time was in excess of four hundred hours. During this period, wide variations of temperature, humidity, barometric pressure, and wind velocity were experienced. Correlation of the measured charging current with any of the atmospheric conditions encountered was not possible. The average value of the charging current was small (in the order of -20 nanoamperes).

An evaluation regarding the effect of rain and wet snow did not materialize because the blade insulation (resistance) could not be maintained for these conditions. Dry snow was not encountered in the test program. A test conducted with sand introduced in the vicinity of the main rotor test stand showed that the normal negative charging current was reduced, indicating that sand produced a positive charging current.

A SH-3A type helicopter, equipped with an insulated main rotor blade, was hovered in clear air and a dust environment. In clear air, the rotor blade charging current was the same order of magnitude as the test stand data (-20 nanoamperes) as compared to a total current of approximately +2 microamperes. When the amount of power that each engine contributed to the total aircraft power was varied, the total aircraft current was affected 10 to 15 percent; the maximum charging current occurred when both engines shared the load equally. In the dust environment, the average rotor blade current was +2.8 microamperes, resulting in a total blade contribution of +14 microamperes (number of blades multiplied by the average current from one blade) as compared to a total helicopter current of +16 microamperes.

CONCLUSIONS

Under clear-air conditions (no snow, dust, sand, rain, etc.), the electrostatic charging current due to main rotor blades was relatively small (-20 nanoamperes) compared to the helicopter's total current (+2 to +3 microamperes). The static electricity associated with the SH-3A helicopters under these conditions consists of charging currents apparently resulting from the engine(s).

Under environmental conditions (snow, dust, sand, rain, etc.), the rotor blades were the major contributors of electrostatic charging currents. However, some qualifications to the preceding statement must be made because the limited flight testing considered only the dust environment while hovering. It is reasonable to conclude that other particles in the atmosphere (snow, sand, rain, etc.) would produce charging currents that predominate. Measurements of blade charging current under conditions of snow, sand, or hail require additional testing.

The testing conducted under this contract did not reveal any recommendation for design changes that would have an influence on charging current.

RECOMMENDATIONS

It is recommended that a study of the alternating currents, observed during this test, be made. These currents appeared periodic in nature, changed with aircraft and environmental conditions, and were normally much larger than the measured direct currents. The study should endeavor to determine the causes of the large alternating currents and how they relate to aircraft charging current in the same type of helicopter in which they were observed.

Testing with an improved insulation system should be conducted to determine the effects of environmental and blade design parameters on the effect of charging current.

The nature of the apparent current observed from the engine(s)' exhaust should be determined.

INTRODUCTION

STATEMENT OF THE PROBLEM

The existence and the seriousness of the electrostatic phenomenon pertaining to aircraft are not new but they have been recognized for many years. Initial investigation began because of the detrimental effects on communications and navigational equipment of fixed-wing aircraft. These investigations were directed toward controlling the intensity, distribution, and character of the corona discharge which is associated with a large accumulation of charge.

The introduction of the helicopter as a vehicle for transporting cargo externally has broadened the problem because of the danger of the electrostatic charge discharging through combustible or explosive types of cargo or ground personnel. The danger arises because of the ability of the helicopter to store electrical energy by means of its capacitance to earth. This stored energy is measured in joules and for all practical purposes is proportional to the size and altitude of the aircraft times the square of the voltage. The energy level determines the degree of electrical discharge to which the ground personnel or cargo might be exposed.

It has been theorized that the three basic charging mechanisms responsible for the electrostatic charge developed on the helicopter are:

1. The main rotor blades.
2. The charge particles (ions) emitted by the engine(s) exhaust.
3. Charged clouds and the earth's electric field.

Of the three basic charging currents the main rotor blades are considered to be the chief generators.

Since static electricity presents a serious problem to ground handling personnel, efforts are directed toward the following:

1. Determining the relative value of the (electrostatic) charging current due to main rotor blades.
2. Determining the parameters and factors that influ-

ence the charging current.

3. Correlating the charging current due to main rotor blades and the total charging current of a helicopter.

4. Determining whether any changes, based on conclusions of this testing, can be incorporated into future designs to reduce the problem of static electricity charge accumulation.

CONTRACT SPECIFICATIONS

Sikorsky Aircraft was authorized to undertake a measurement program at the Contractor's facility to determine the electrostatic charging currents due to main rotor blades and to determine the significant parameters affecting the value of the charging current. The statement of work of the contract originally consisted of test stand measurements with an insulated main rotor blade, but was later expanded to cover a three-hour flight test measurement program.

The test stand measurements consisted of measuring the electrostatic charging current from two electrically insulated main rotor blades that would be whirled over a long period of time in order to obtain measurements under various environmental conditions. The flight test measurements consisted of measuring the electrostatic charging current from an electrically insulated main rotor blade that would be flown on a twin-engined SH-3A type helicopter at various altitudes and engine power conditions. Total aircraft-to-ground charging currents would also be measured.

EXPERIMENTAL PROCEDURE

INSULATION OF THE MAIN ROTOR BLADE

The insulating material of the blades consisted of various forms of mylar, fiberglass, and synthane. Details of the methods used are illustrated in Figures 1 and 2. Considerable difficulty was experienced while insulating the SH-3A type blade. After the initial assembly, the insulation resistance was 40,000 ohms, and not the 100,000 ohms necessary to keep the measurement system errors low. Disassembly revealed that the mylar tape which lined the inside of the cuff was pushed back slightly and that the nylon sleeve near the threaded portion of the bolts was torn. The nylon sleeve was replaced with mylar tape, and the cuff lining was replaced with a thinner mylar tape. Some minor difficulties with insulation existed after the initial problem, but they were overcome with care exercised during the assembly procedure.

Some difficulty was experienced with the insulation of the SH-3A main rotor blade on the aircraft, but after several attempts, the blade was successfully insulated. The insulation remained satisfactory for the entire test program.

The CH-34 main rotor blade, which was tested on the 2000-horsepower test stand, was easily insulated because of the type of blade attachment to the rotor head. No problems existed with the insulation throughout the entire test program.

The specifications of blades that were insulated and tested are listed in Table 1.

TABLE 1
BLADE SPECIFICATIONS

	Helicopter Models	
	CH-34	SH-3A
Length (in.)	307	337
Chord (in.)	16.4	18.3
Area (sq. in.)	5040	6414

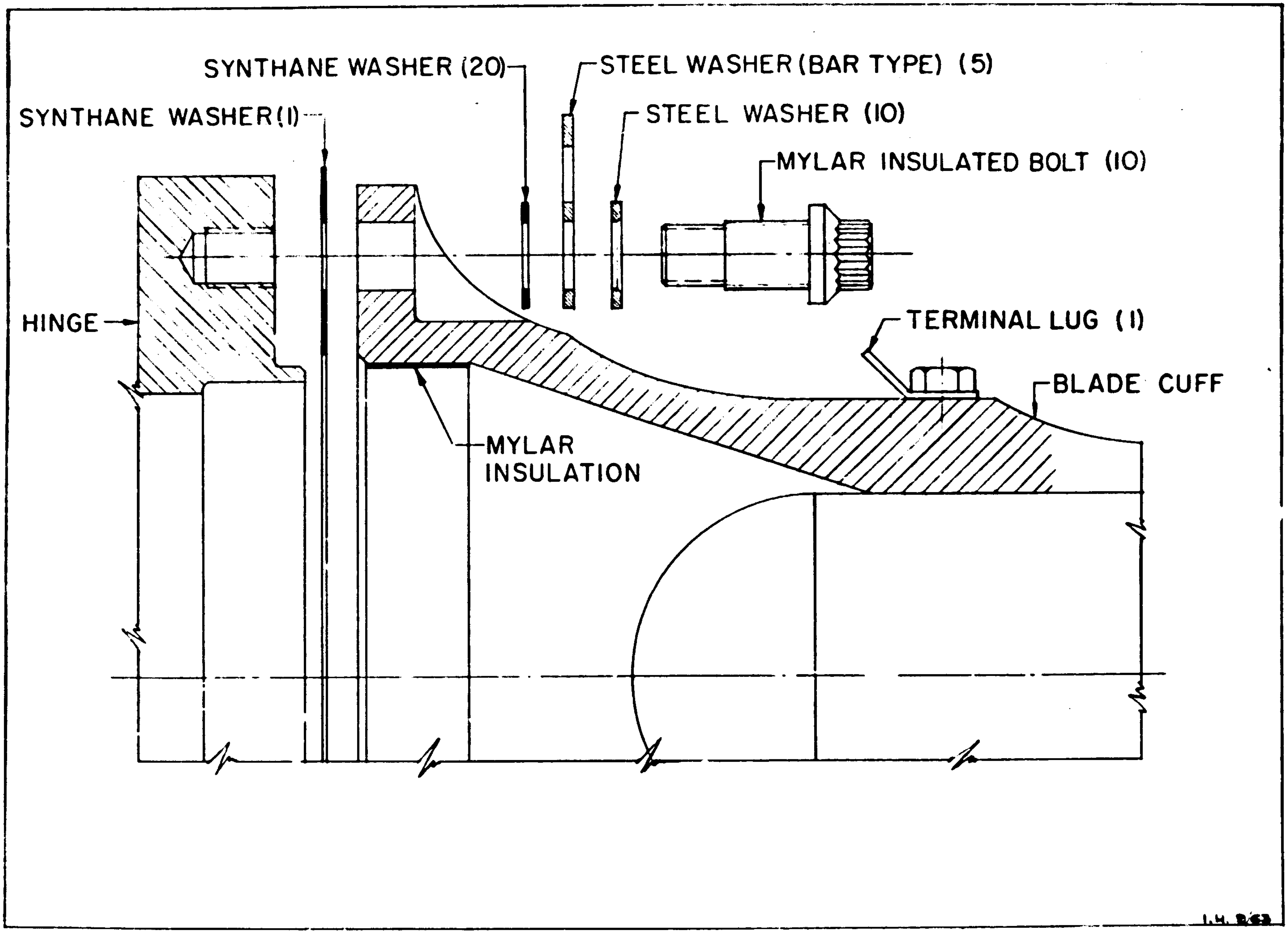

FIGURE 1. INSULATION OF SH-3A TYPE MAIN ROTOR BLADE.

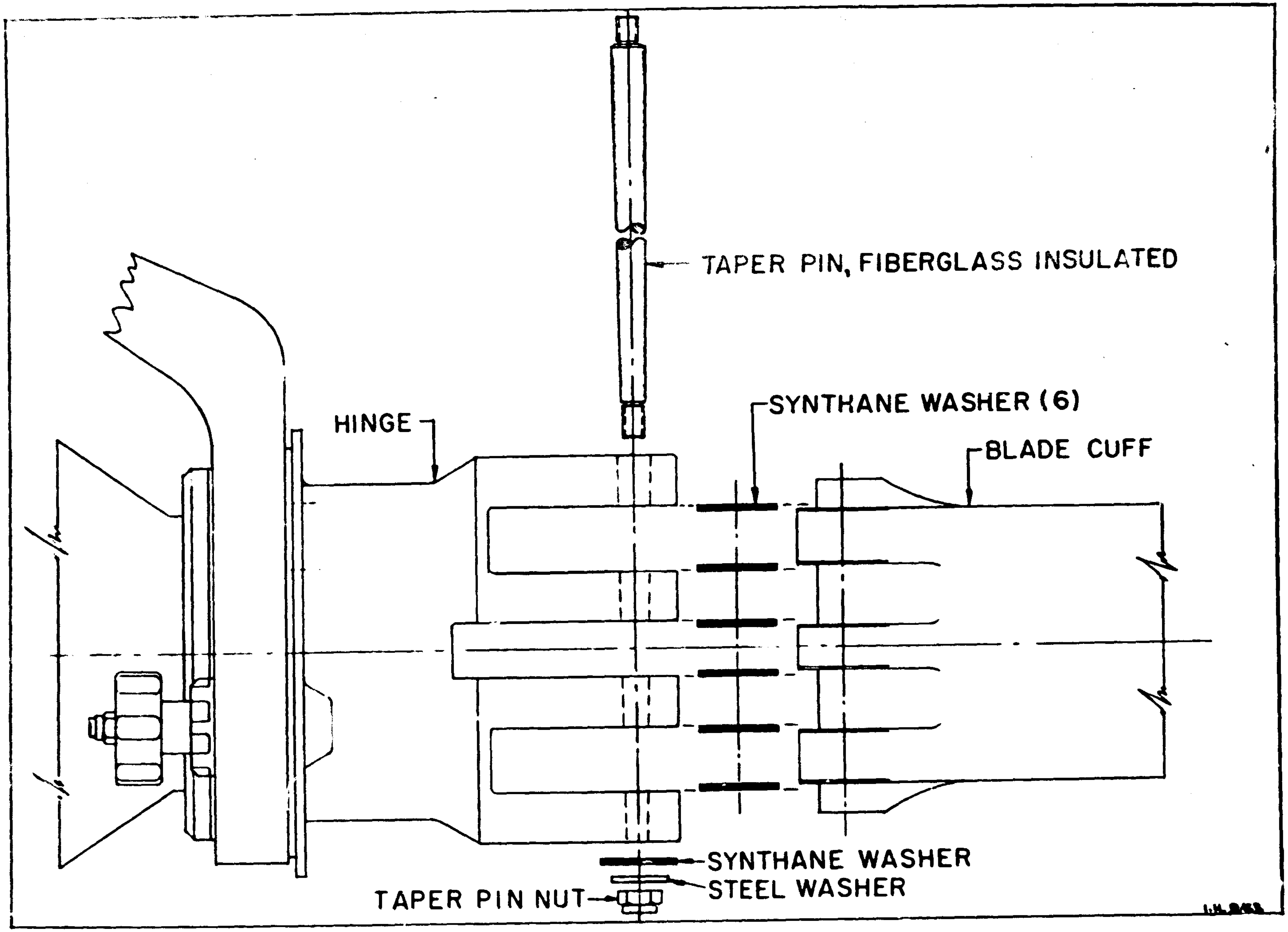

FIGURE 2. INSULATION OF CH-34 TYPE MAIN ROTOR BLADE.

MEASUREMENT SYSTEMS

The measurement systems for the test stands and aircraft tests were designed on the basis that the charging mechanism is a current source (a source with a high resistance). The systems were of basic design (Figures 4 and 5) utilizing standard instrumentation components consisting of slip rings, a DC amplifier shunted by a 1000-ohm precision resistor, and a recorder. In addition, each system was provided with a method of checking the insulation of the blade and a simple calibration circuit.

Initial testing on the test stand revealed the need for a threshold of 1 nanoampere rather than the 10 nanoamperes originally considered. The lowering of the threshold caused concern for the validity of the measurement system. The measurement systems were validated by simulating a current source on the blade using a 100-megohm resistor and a battery. This test showed that if a current was flowing between the insulated blade and rotor head, it would be measured to an accuracy of $\pm 1\%$ of full scale. Additional tests were conducted to verify the fact that the current generated by the blade was a current source. Values of the input resistance of the measurement system were varied from 1000 ohms to 1 megohm, and no change in charging currents was observed. The shunt resistance to ground was greater than 100 megohms during the test.

Ground runs prior to aircraft tests showed the requirement for a filtered insulated blade current trace as well as an unfiltered trace. The threshold of the unfiltered system was in the order of one-half of a microampere. A filter was designed with a cutoff frequency of 0.5 cycle per second, and the threshold was improved to ± 3 nanoamperes. Figure 3 is a schematic diagram of the filter.

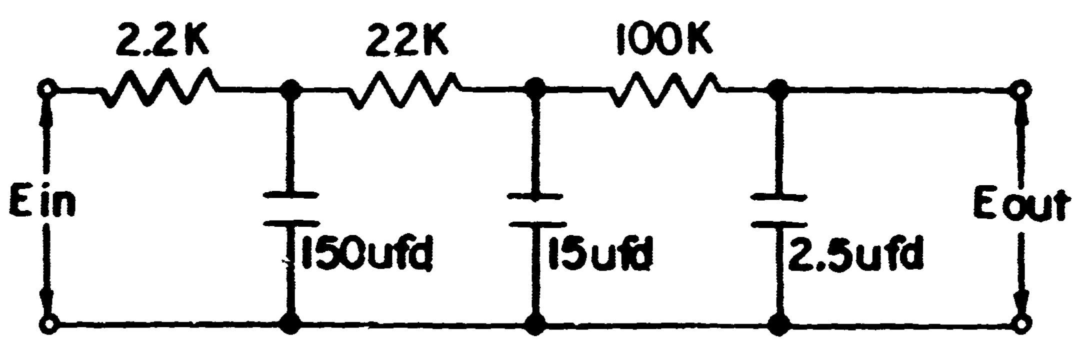

FIGURE 3. FILTER CIRCUIT.

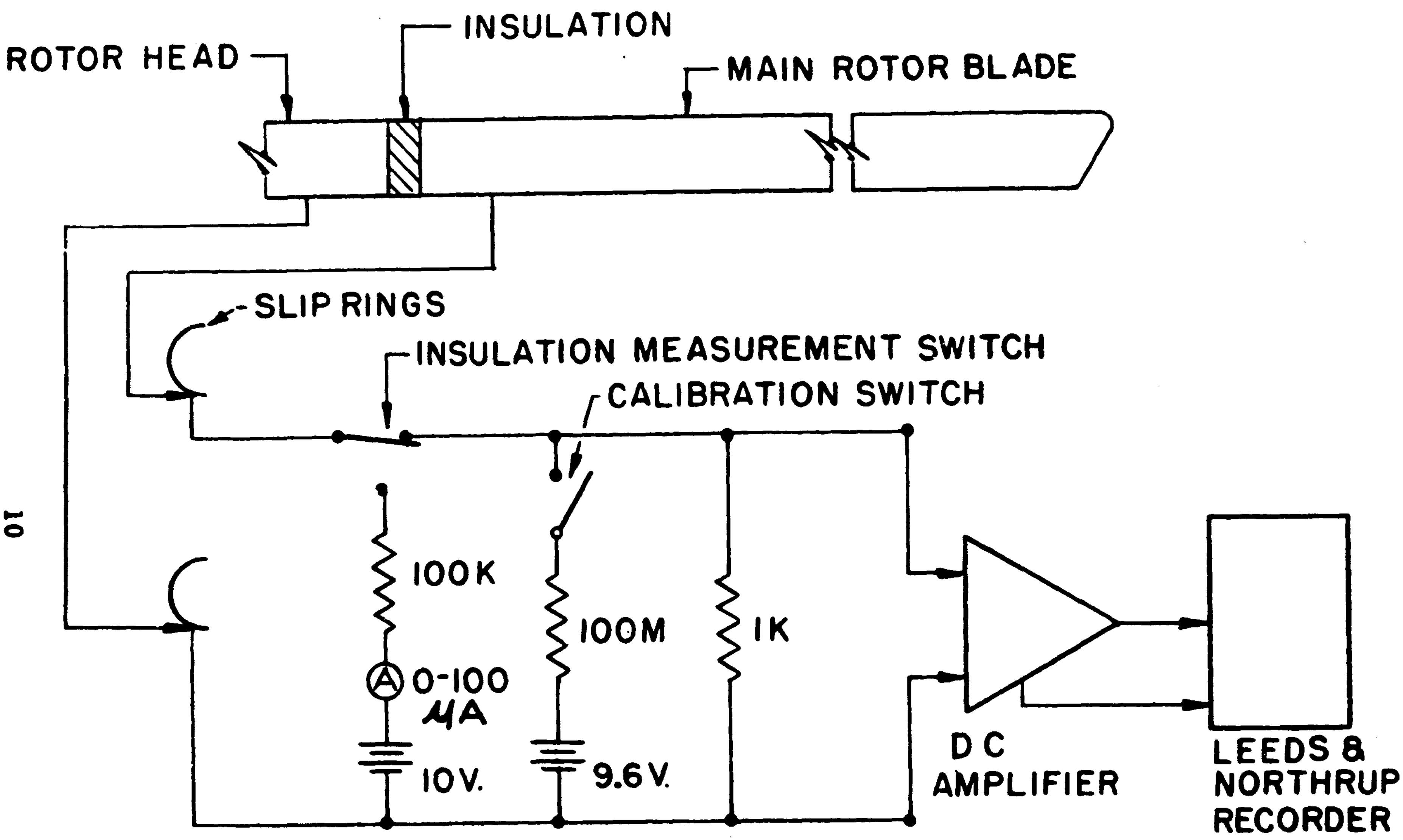

Figure 4. Measurement System for Main Rotor Test Stand.

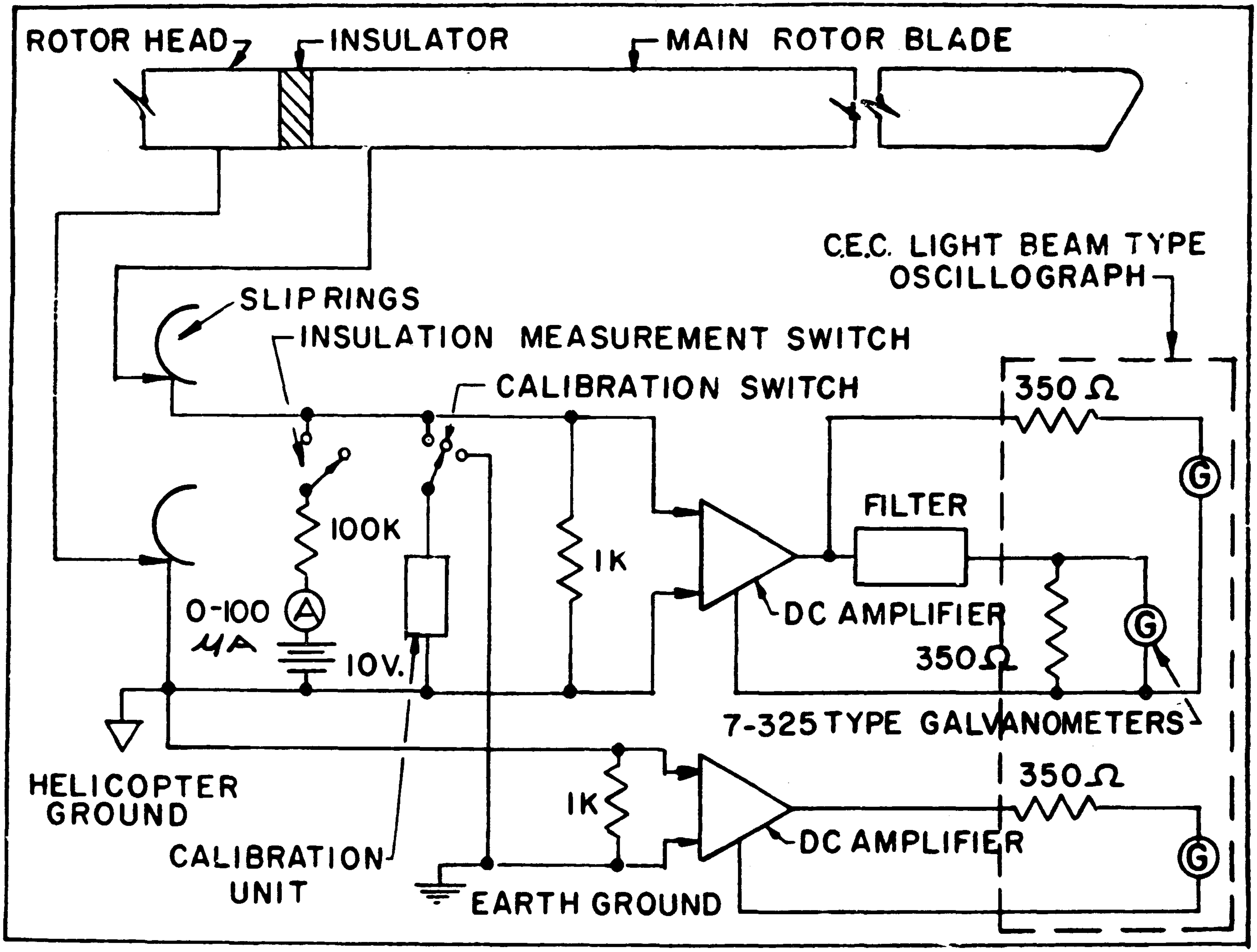

Figure 5. Measurement System for SH-3A Helicopter.

Calibration of the measurement system was performed at the beginning and end of each test. Certification of the calibration equipment was performed by the Measurement Standards Laboratory, which maintains standards traceable to the National Bureau of Standards.

EXPERIMENTAL RESULTS

TEST STAND

The main rotor test blades were subjected to various blade angles, rotor speeds, rotor powers, and atmospheric conditions. The following information was recorded in a daily log:

1. Electrostatic charging current.

2. Operating parameters of the test facility.

3. Meteorological conditions.

4. Degree (resistance) of blade insulation.

5. Notation of unusual occurences.

The rotor test stand testing commenced on a 1500-horsepower blade balance stand (Figure 6) during the latter part of September 1962, and continued periodically until January 1963, using the insulated SH-3A type main rotor blade. The charging currents never exceeded -3 nanoamperes under any condition. (The conventional definition of direction of current is used throughout the report; that is, a + sign denotes a current which flows from a positive to a negative potential.) It was suspected that the measured current was not a realistic blade charging current, but some characteristic of the test stand.

This suspicion was verified after the SH-3A type blade was replaced with a CH-34 type blade, which was being subjected to the same tests on a 2000-horsepower main rotor test stand (Figure 7). The same blade charging current (never exceeding -3 nanoamperes) was observed. This CH-34 type blade had been experiencing blade charging currents averaging -30 nanoamperes and occasionally reaching peaks of -60 nanoamperes on the 2000-horsepower main rotor test stand. It was not feasible to test the SH-3A type blade on the 2000-horsepower main rotor test stand because the rotor head was not capable of handling this larger blade.

More than 400 test hours were recorded during the period from October 1962 to April 1963, using the insulated CH-34 main rotor blade on the 2000-horsepower main rotor test

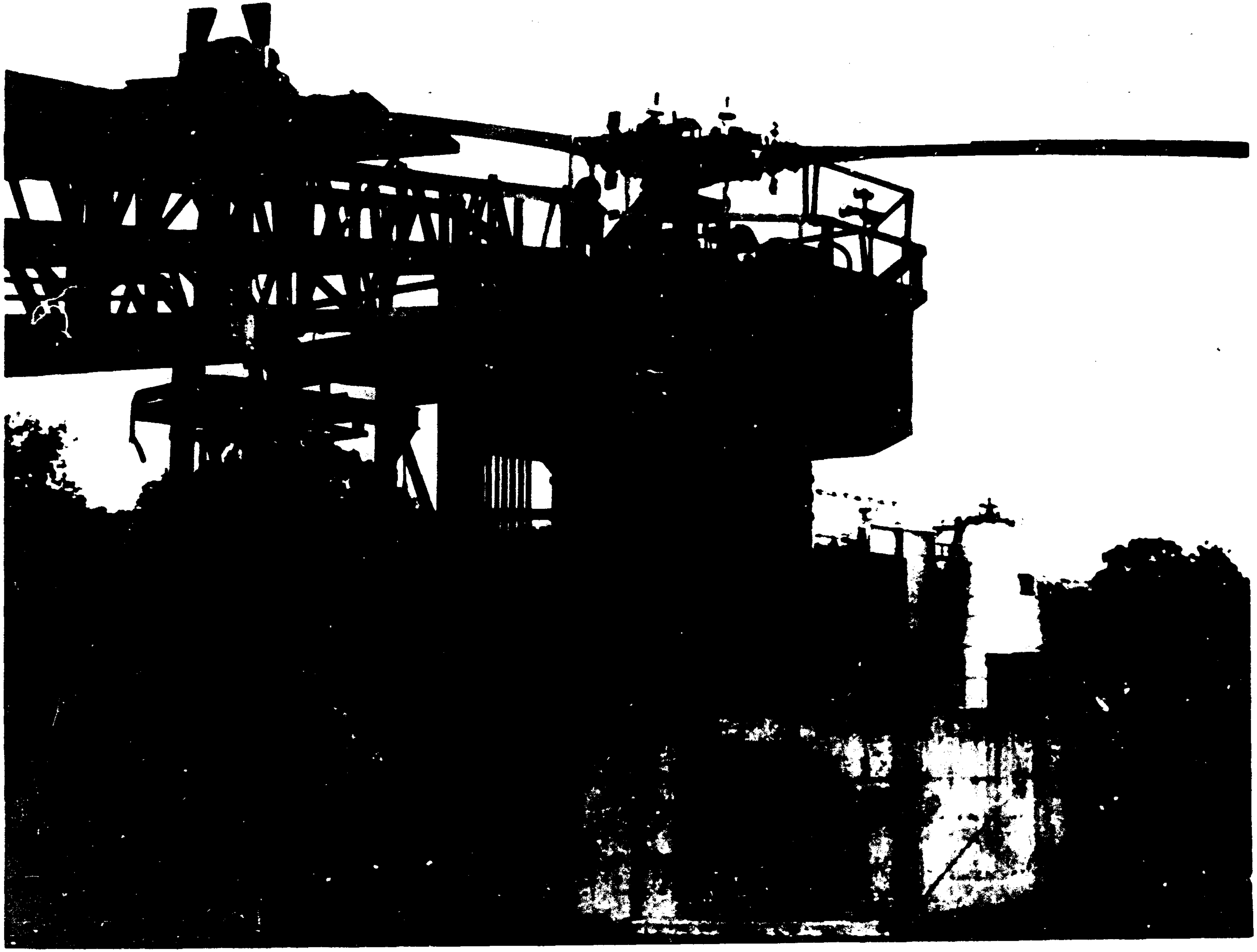

FIGURE 6. 1500 HORSEPOWER BLADE BALANCE STAND.

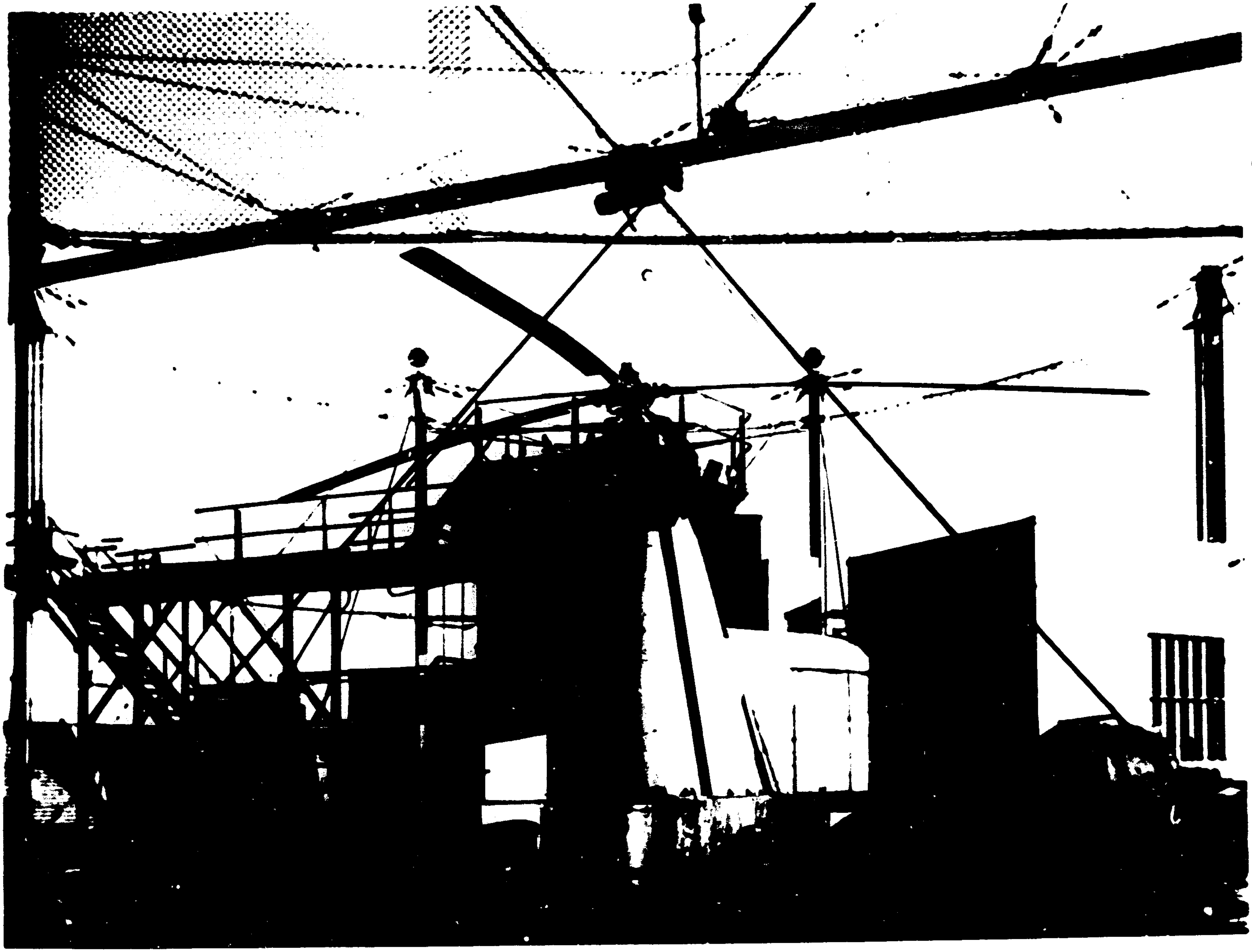

FIGURE . 2000-HORSEPOWER MAIN ROTOR TEST STAND.

stand under the atmospheric and test stand conditions listed in Tables 2 and 3. A typical recording is shown in Figure 8, which illustrates the charging current, test stand operating conditions, and atmospheric conditions. The record shows that the average charging current is approximately -20 nanoamperes.

Figures 9 through 11 are presented to show that with changes in atmospheric and test stand conditions, no appreciable change in charging currents occurred.

Figure 12 shows the effect of charging current on the blade initially coated with a quarter of an inch of ice and the gradual shedding of the ice. The charging current at the beginning of the test was +50 nanoamperes. The current then fluctated around an average of -15 nanoamperes, changed polarity, and stabilized at an average of -23 nanoamperes. The reason for the positive charge probably lies in the difference of the dielectric constant of an ice-coated blade and the normal blade finish (Coehn's Law). Figure 13 shows the effects of charging current on the blade initially coated with a light layer of ice.

Figure 14 is a record showing what effect sand had on the charging current when it was introduced into the rotor system. Sand reduced the normal negative charging characteristic, implying that sand has a positive charging property. Quantitative results showing the amount of sand versus the charging current can not be presented because it was relatively impossible to measure the amount of sand striking the blade.

TABLE 2 ATMOSPHERIC CONDITIONS	
Temperature	0 to 95°F
Wind	0 to 50 knots
Humidity	20 to 100%
Weather (General)	Clear to cloudy
Precipitation	Rain and wet snow

TABLE 3 TEST STAND CONDITIONS	
Rotor Speed	0 to 221 rpm
Thrust	1000 to 10,000 pounds
Blade Flapping	$\pm 5\frac{1}{2}$ degrees

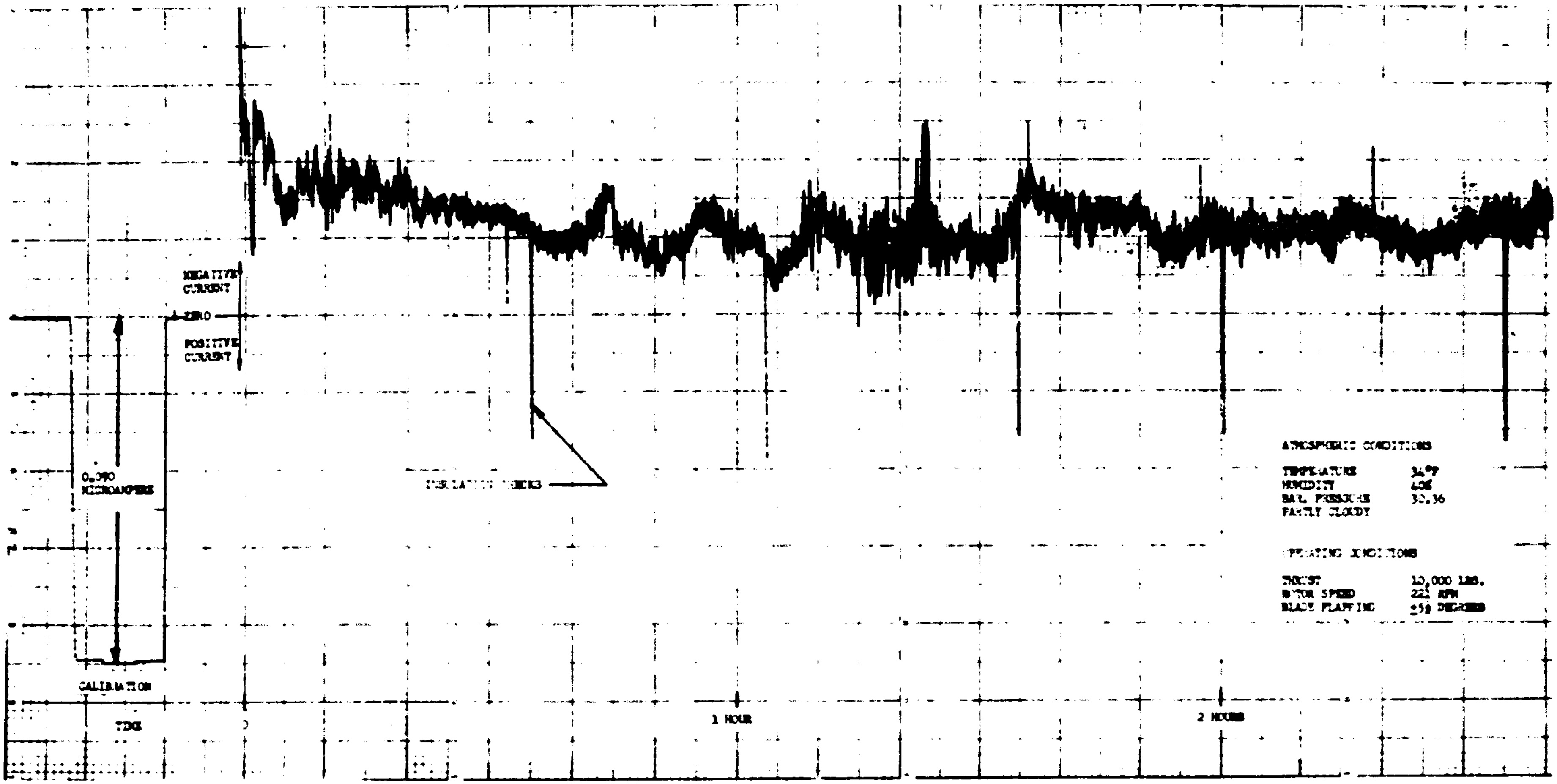

FIGURE 8. CHARGING CURRENT ON CH-34 TYPE MAIN ROTOR BLADE - NORMAL ATMOSPHERIC CONDITIONS.

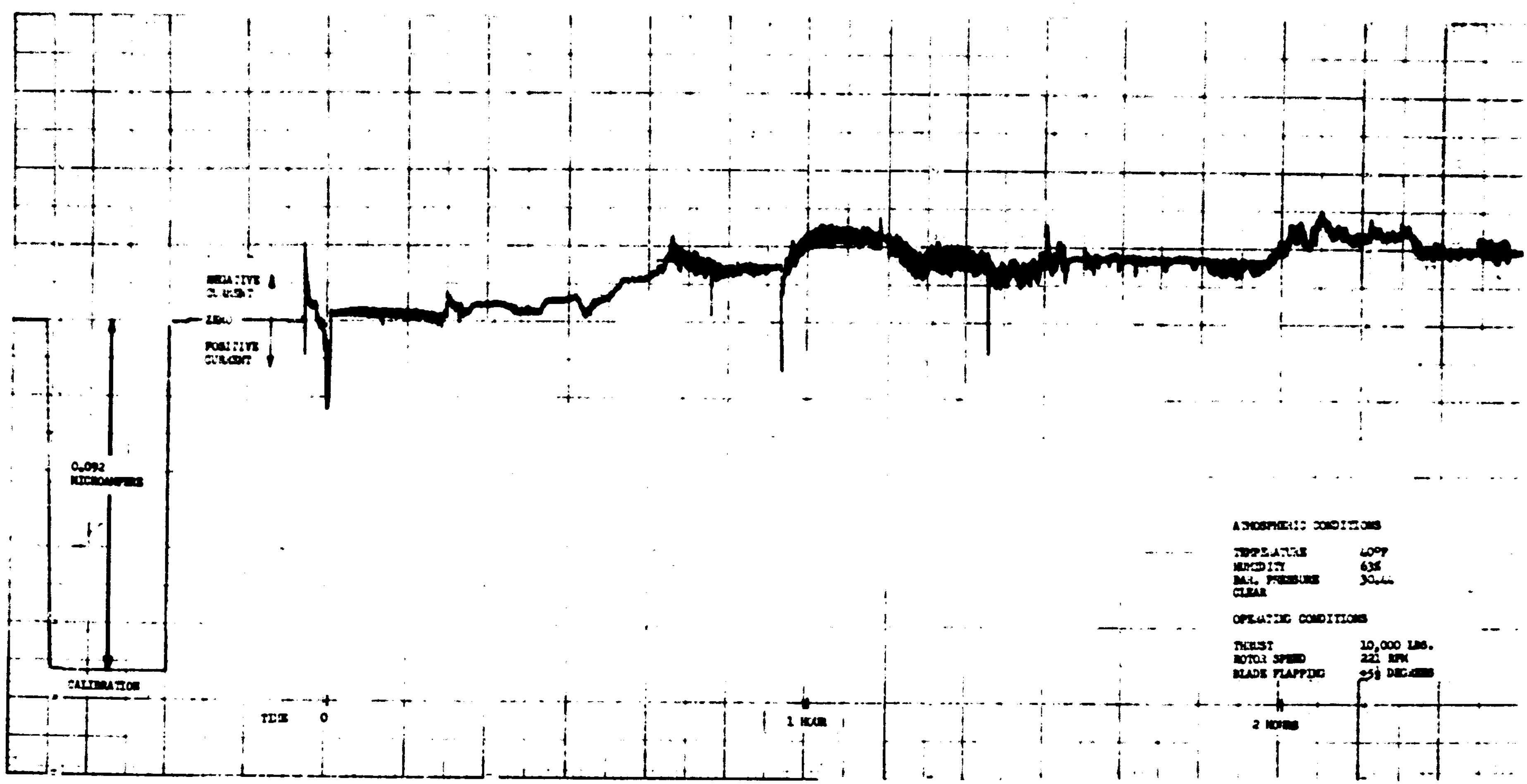

FIGURE 9. CHARGING CURRENT ON CH-34 TYPE MAIN ROTOR BLADE - NORMAL ATMOSPHERIC CONDITIONS.

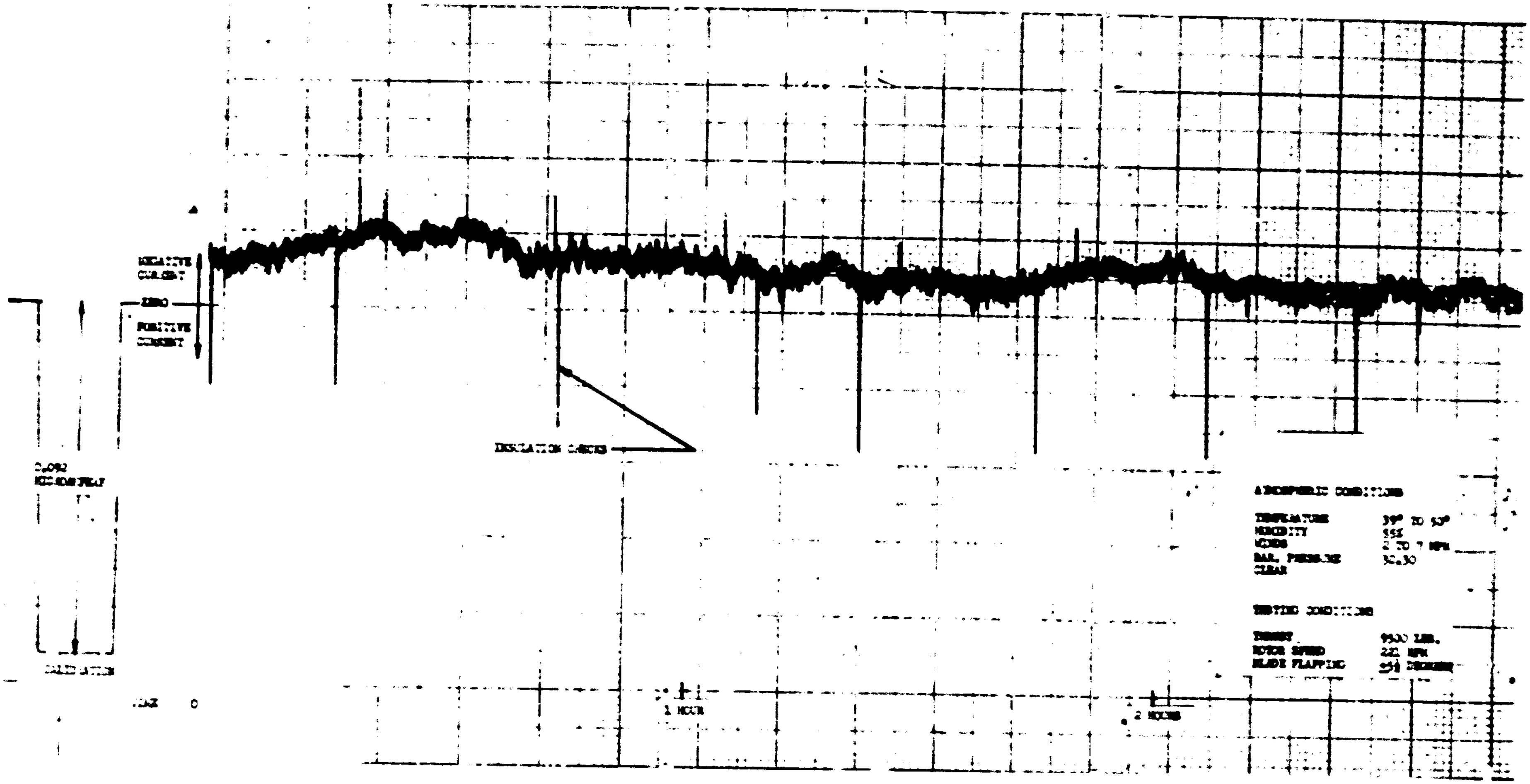

FIGURE 10. CHARGING CURRENT ON CH-34 TYPE MAIN ROTOR BLADE - NORMAL ATMOSPHERIC CONDITIONS.

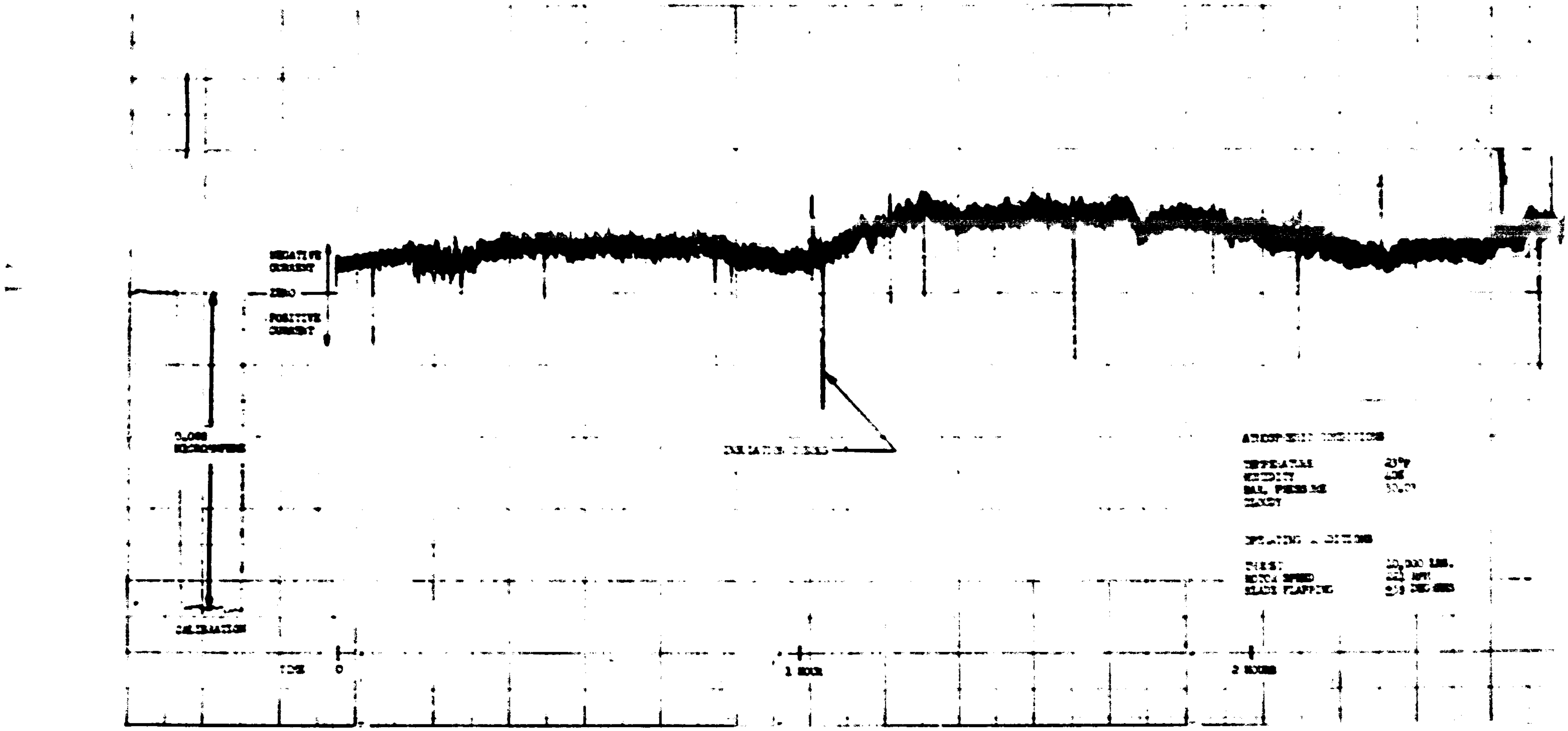

FIGURE 11. CHARGING CURRENT ON CH-34 TYPE MAIN ROTOR BLADE - NORMAL ATMOSPHERIC CONDITIONS.

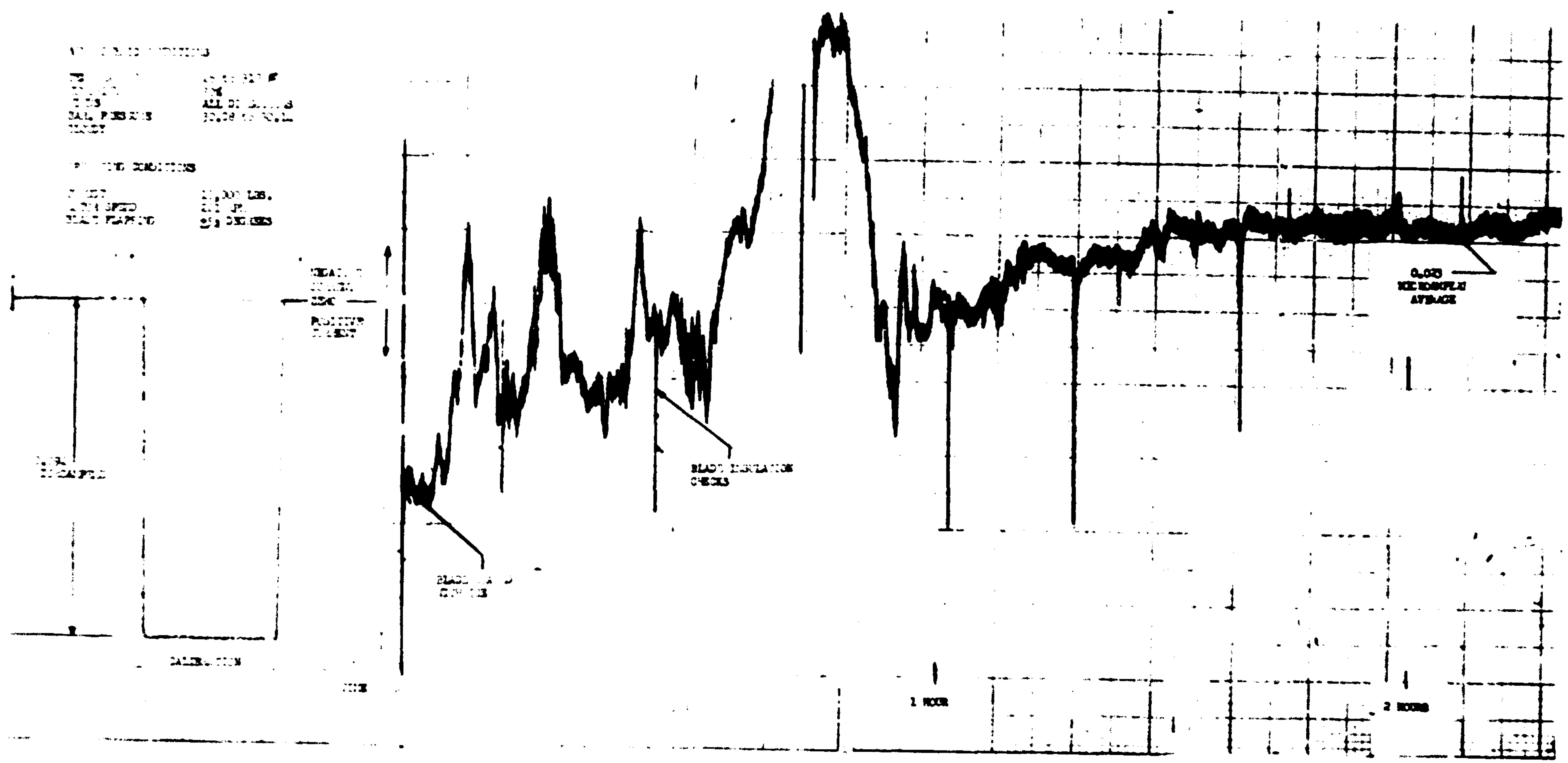

FIGURE 12. CHARGING CURRENT ON CH-34 TYPE MAIN ROTOR BLADE - INITIALLY COATED WITH ICE.

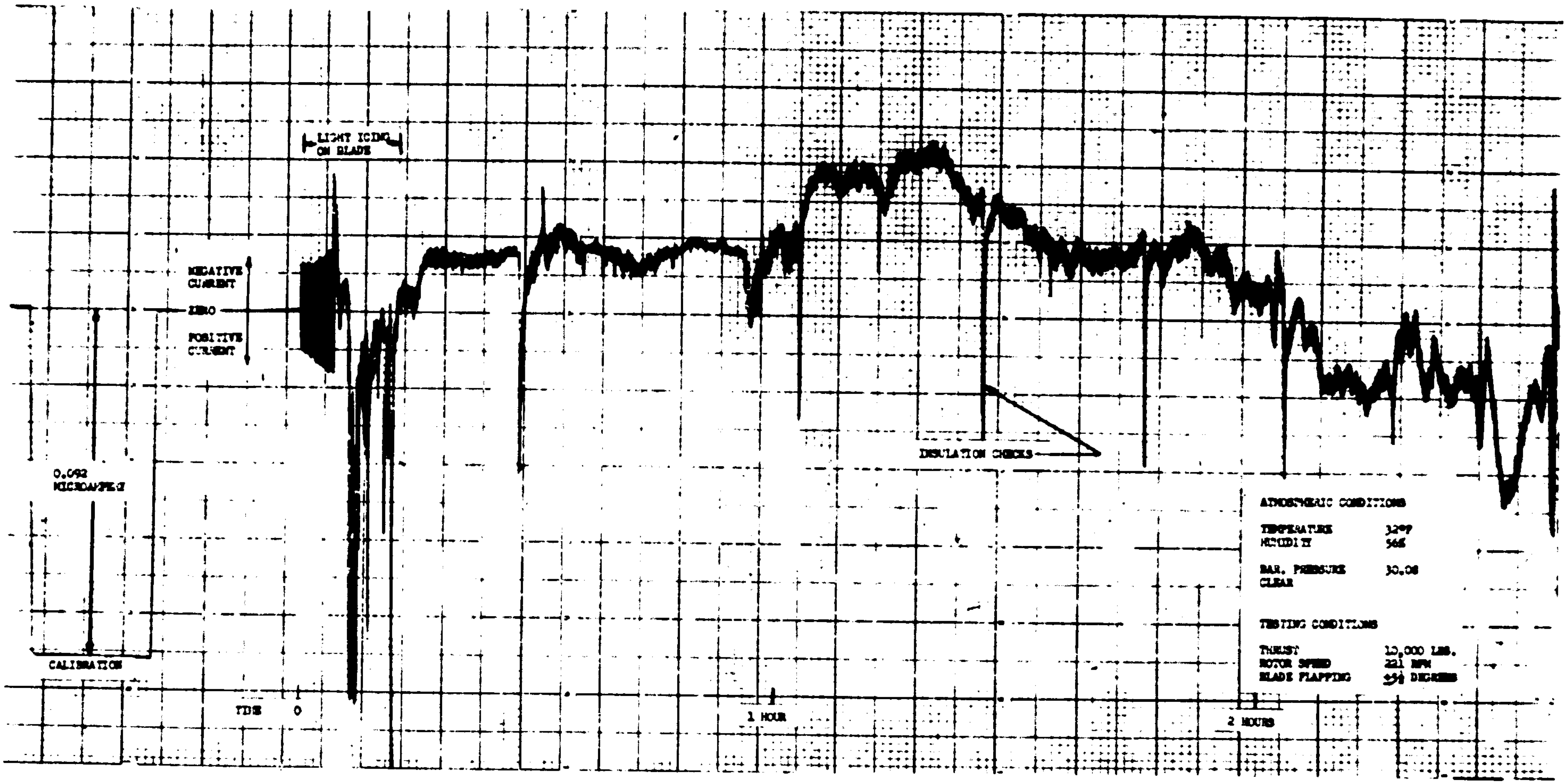

FIGURE 13. CHARGING CURRENT ON CH-34 TYPE MAIN ROTOR BLADE - INITIALLY COATED WITH LIGHT LAYER OF ICE.

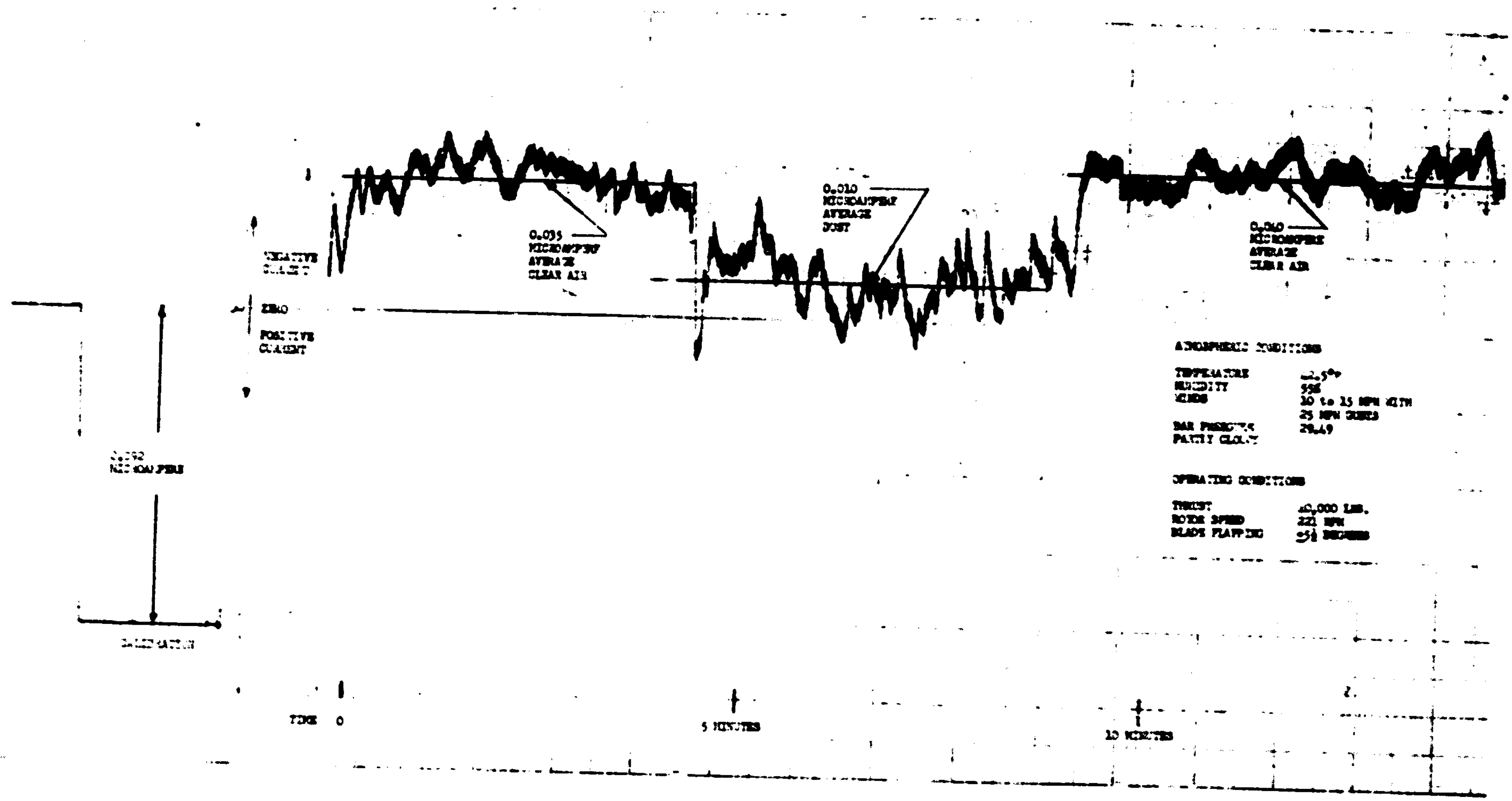

FIGURE 14. CHARGING CURRENT ON CH-34 MAIN ROTOR BLADE - DUST CONDITIONS.

AIRCRAFT TESTS

A model SH-3A Sikorsky helicopter (Figure 15), equipped with twin 1250-horsepower (military) General Electric T-58 engines, was used to conduct the investigation to determine the magnitude and polarity of the main rotor blade current with respect to total helicopter current. The helicopter, equipped with the insulated main rotor blade that was used on the 2000-horsepower main rotor test stand, hovered over the ground at various altitudes ranging from 25 to 100 feet. At each altitude, the percent of power applied by each engine was varied. Table 4 is a tabulation of main rotor blade currents and total helicopter currents recorded at various altitudes and power settings in clear air. The table shows that current due to the main rotor blade is negligible compared to total helicopter current. It also shows that when power settings were altered, the total helicopter current varied from 10 to 15 percent; the maximum change occurred when both engines shared the load equally.

Three additional hovering flights were conducted to check the validity of the measurements recorded for the first flight. Results of the additional flights basically verified the measurements observed during the first flight. Total helicopter average current varied from +1.4 to +2.0 microamperes, with main rotor blade currents ranging from 0 to -20 nanoamperes. During one of these flights, the helicopter hovered over water and the polarity of the main rotor blade current changed from negative to positive, but was of the same magnitude of the test conducted over the concrete flight field. No values of total helicopter current were obtained because of a malfunction in the measuring system.

Two hovering flights were conducted in a dust environment. Ten cubic yards of screened dirt was spread over a 2500-square-foot area of the Stratford plant flight field. The first test did not create a dust environment because the dust blew away, resulting in poor dust circulation through the rotor system. Figure 16 shows that a small average main rotor blade current, as well as total helicopter current, was measured. The second test had good dust circulation through the rotor system, and excellent results were obtained. Figure 17 shows that the insulated main rotor blade current multiplied by the number of blades (5) follows the total helicopter current in both direction and magnitude.

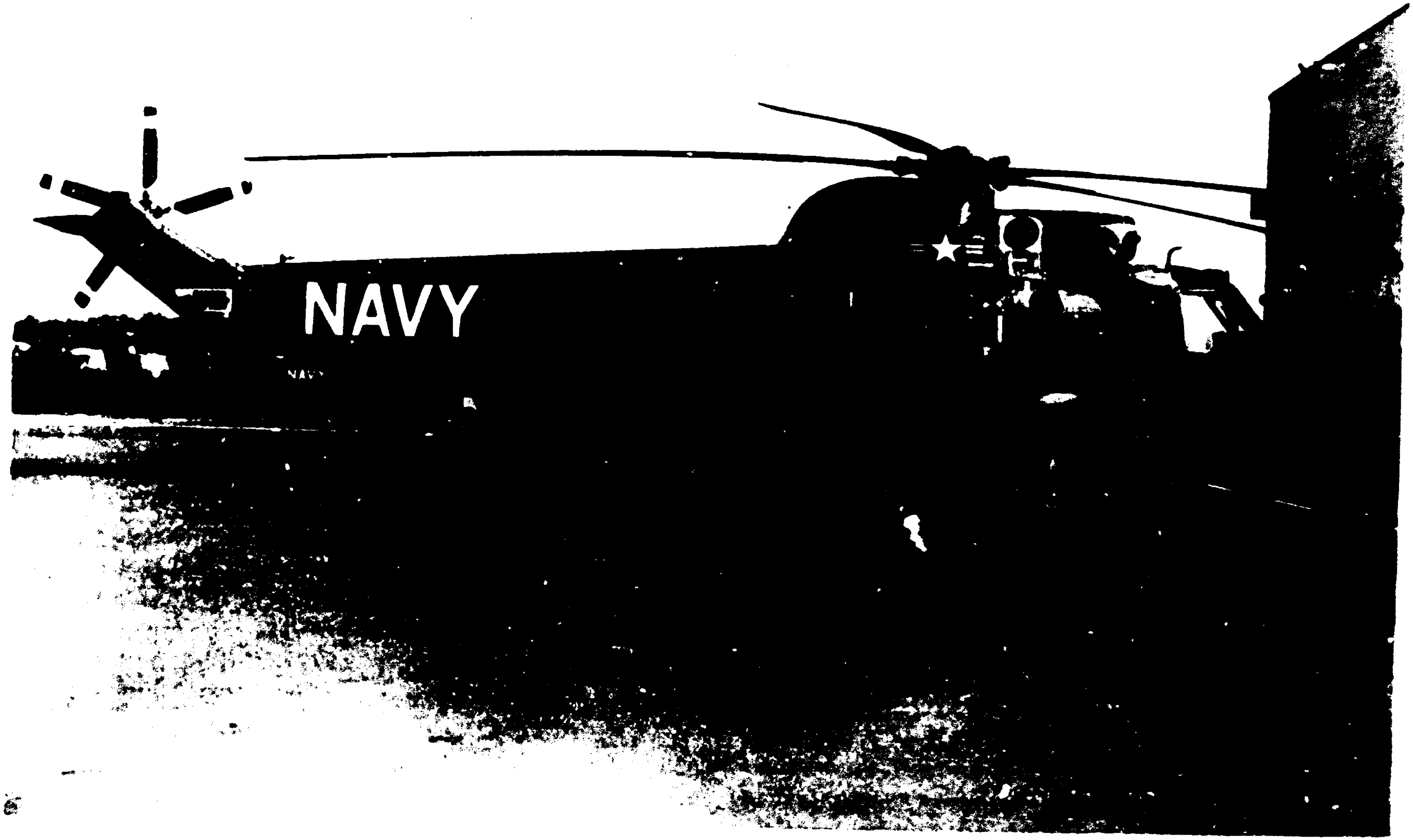

FIGURE 15. SH-3A HELICOPTER .

TABLE 4

TOTAL HELICOPTER AND BLADE CURRENT - CLEAR AIR

Altitude (ft.)	Power Settings (%)		Current (ua)		
	Eng. No. 1	Eng. No. 2	Total Helicopter	Blade (1)	Blade (5)
25	90	15	+1.7	-0.005	-0.025
	50	50	+2.0	-0.005	-0.025
	65	45	+1.9	-0.005	-0.025
50	90	20	+1.8	-0.005	-0.025
	55	55	+1.95	-0.005	-0.025
	65	45	+1.80	-0.005	-0.025
75	90	20	+1.8	-0.005	-0.025
	52	52	+2.1	-0.005	-0.025
	60	45	+2.1	-0.005	-0.025
100	90	20	+1.95	-0.005	-0.025
	52	52	+1.80	-0.005	-0.025
	60	45	+1.80	-0.005	-0.025

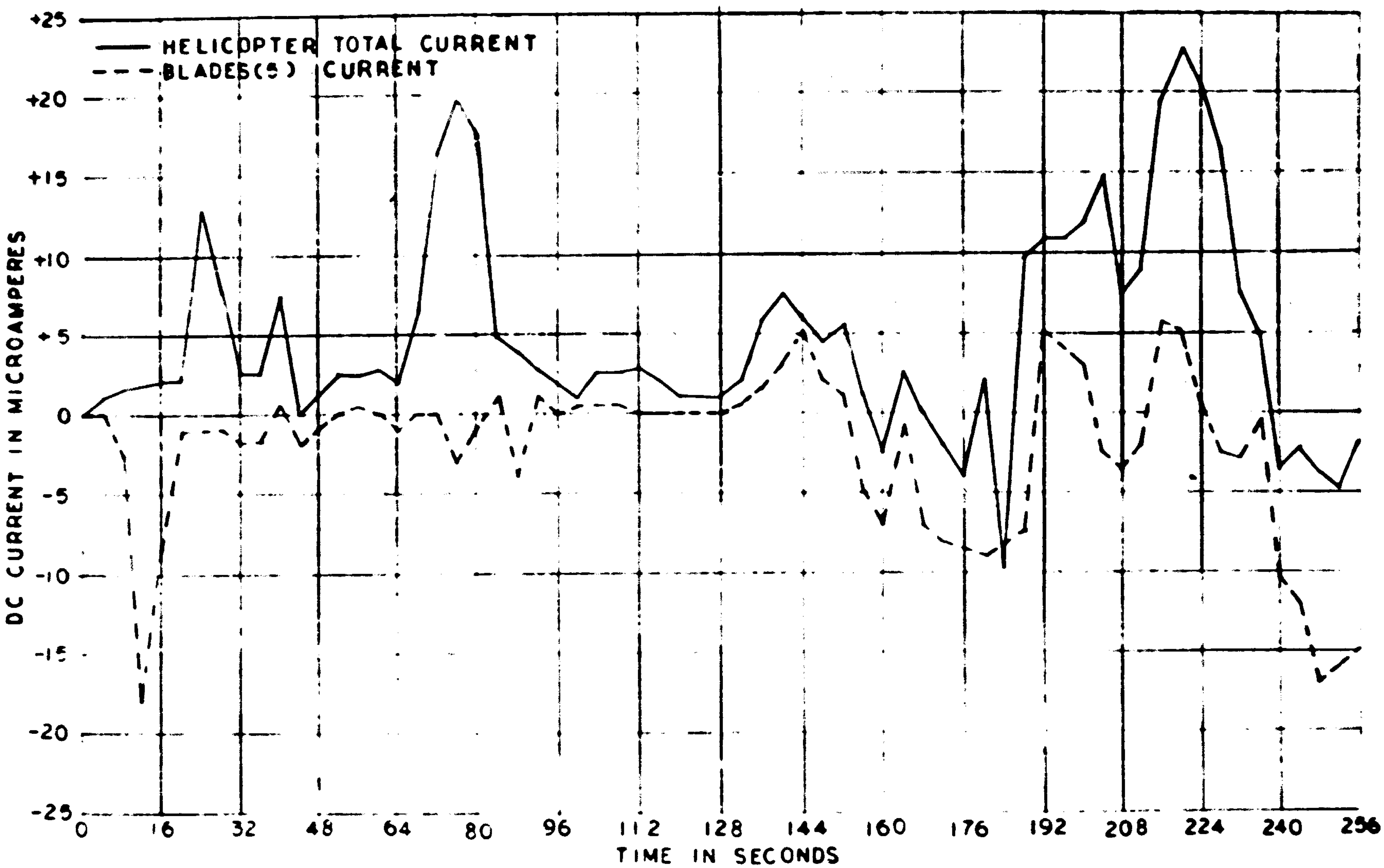

FIGURE 16. CHARGING CURRENT ON SH-3A TYPE AIRCRAFT AND BLADE-DUST CONDITIONS.

The average total helicopter current was + 16 microamperes as compared to + 14 microamperes for the main rotor blades. The difference between the two measurements is the approximate total helicopter current previously measured in clear air. This difference can be attributed to the engines if it is assumed that the charging characteristic of the engines are not affected by the dust.

Average current determinations were obtained by the measurement of the area under the curve using a planimeter. Data points represent readings taken every 4 seconds over a 254-second flight (Figure 16) and every 2 seconds over a 144-second flight (Figure 17).

The total helicopter current traces as well as the blade current traces recorded during the test were characterized by alternating current. The alternating current had a frequency of approximately 16 cycles per second for the total helicopter current and 6.5 cycles per second for the main rotor blade current. This corresponds to 5 times the rotor speed for the aircraft and 2 times the rotor speed for the main rotor blade. A visual examination of the alternating current waveforms recorded on the main rotor blade current trace revealed that the waveforms were basically comprised of 1/rev, 2/rev, and 5/rev components. Assuming that each blade produced identical waveforms of equal magnitude and phase, that the 5 blades are spaced 72 degrees apart, and that the total helicopter current is proportional to the main rotor blade current, it can be shown both mathematically and graphically (Figures 18 and 19) that the summation of the 1/rev and the 2/rev components cancel and do not contribute to the total helicopter current. It can also be shown (Figure 20) that the 5/rev component which appears in each of the 5 main rotor blades add, resulting in the 5/rev alternating current found in the total helicopter current traces. Equation (1) is a general formula which can be used as a mathematical proof.

$$Y = \sum_{N=0}^{N=4} a \sin \left[\theta + MN \, (2\pi/5) \right] \qquad (1)$$

where

M is any frequency which is an integral multiple of the rotor's rotational speed.

θ varies from 0 to 360M.

Peak-to-peak values of total helicopter current, comprised of 5/rev components, ranged as high as 54 microamperes in dust to 1.5 microamperes in clear air. Single-blade current, comprised of 1/rev, 2/rev, and 5/rev components, ranged from a high of 90 microamperes in dust to 4 microamperes in clear air.

Although forward-flight measurements were not required, it was felt that some additional information might be attained by observing and recording the insulated blade currents at helicopter speeds of 20, 30, 50, 60, and 65 knots. The records showed that there was no apparent increase or decrease in the charging current due to forward speed and the current measured was the same as the hovering condition. However, maneuvers such as left and right turns produced a main rotor single-blade current as high as 0.500 microampere. It was not possible to measure the total helicopter charging current during these tests.

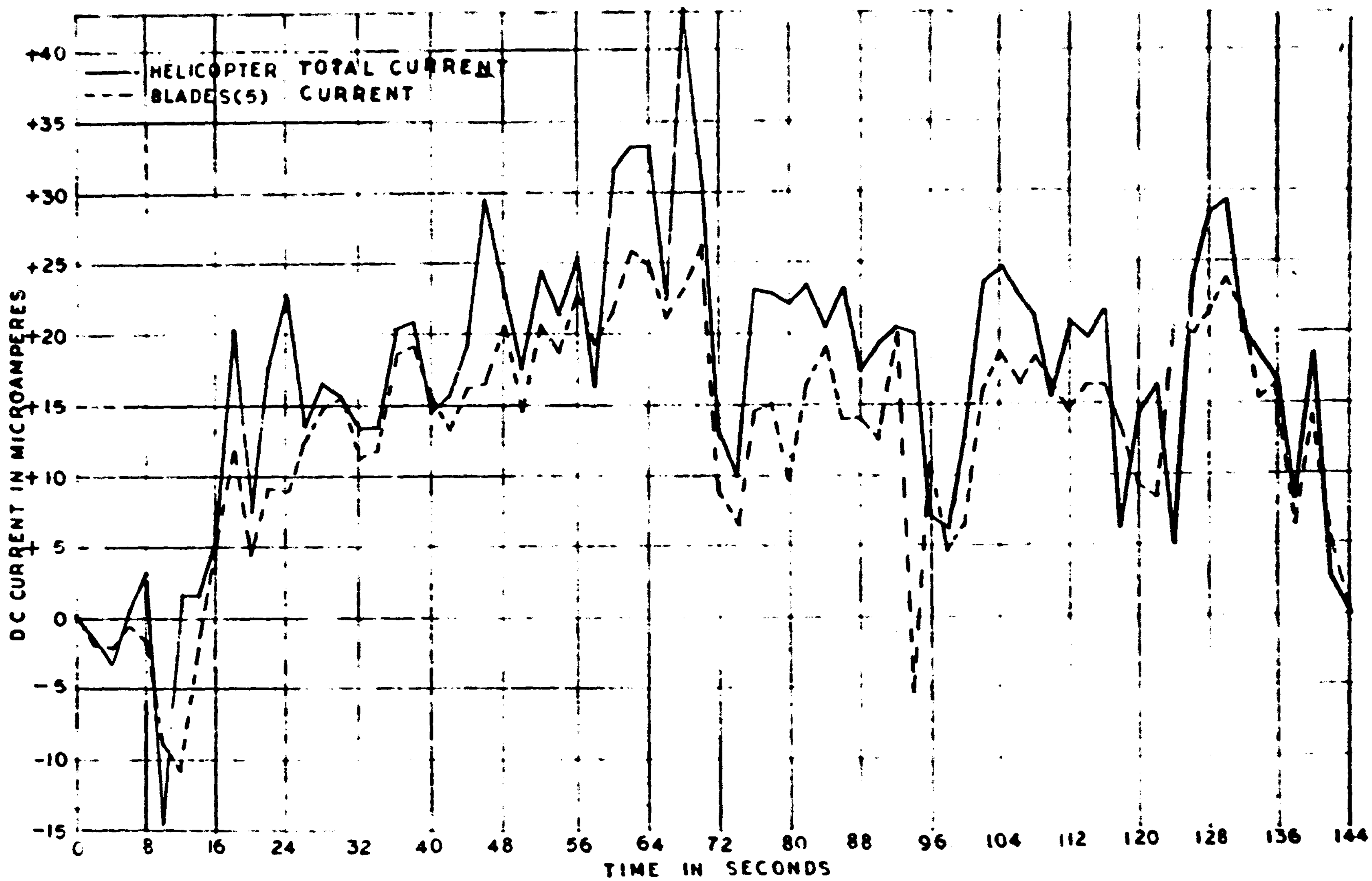

FIGURE 17. CHARGING CURRENT ON SH-3A TYPE AIRCRAFT AND BLADE-DUST CONDITIONS.

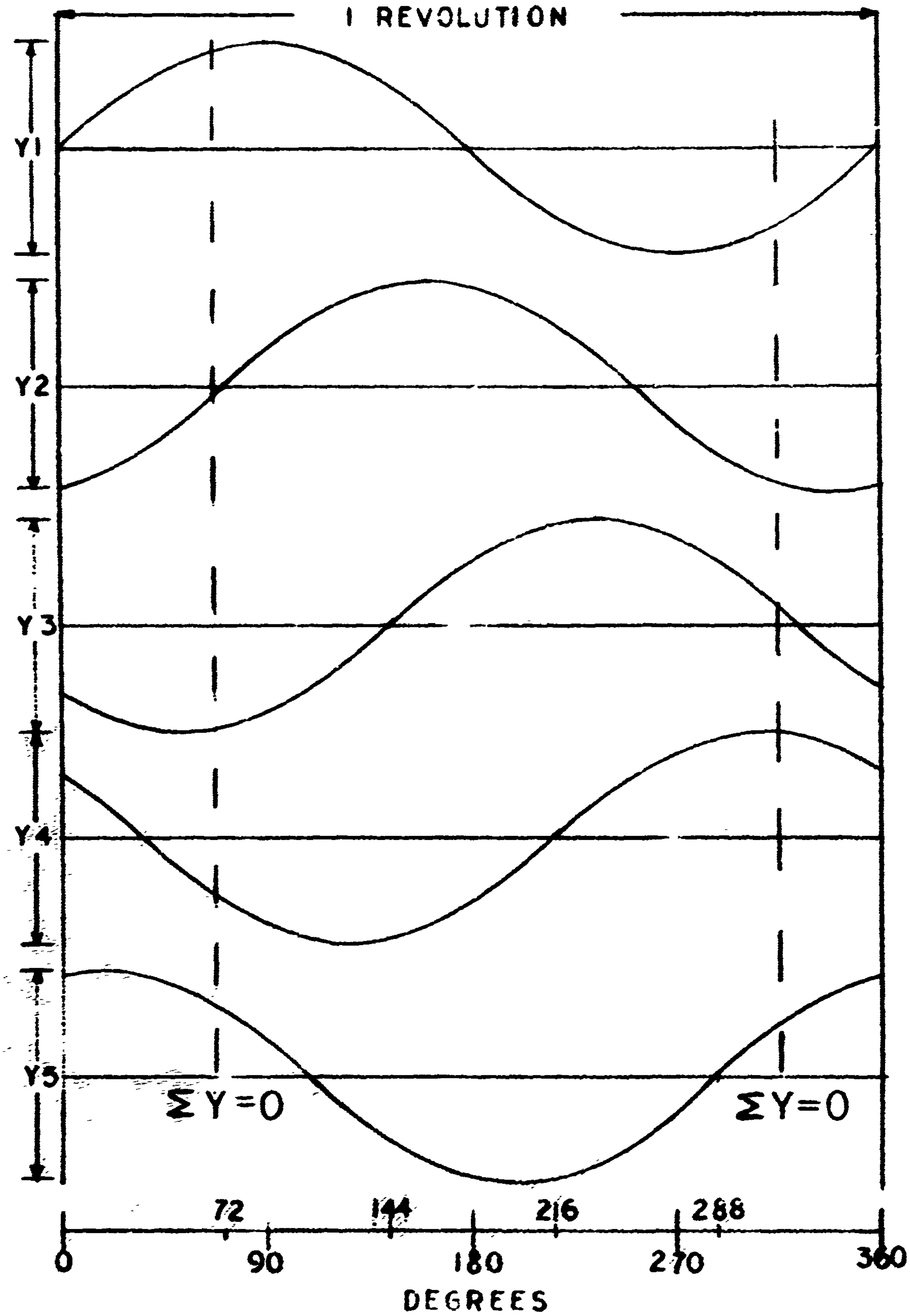

FIGURE 18. A C BLADE CURRENT - 1/REV

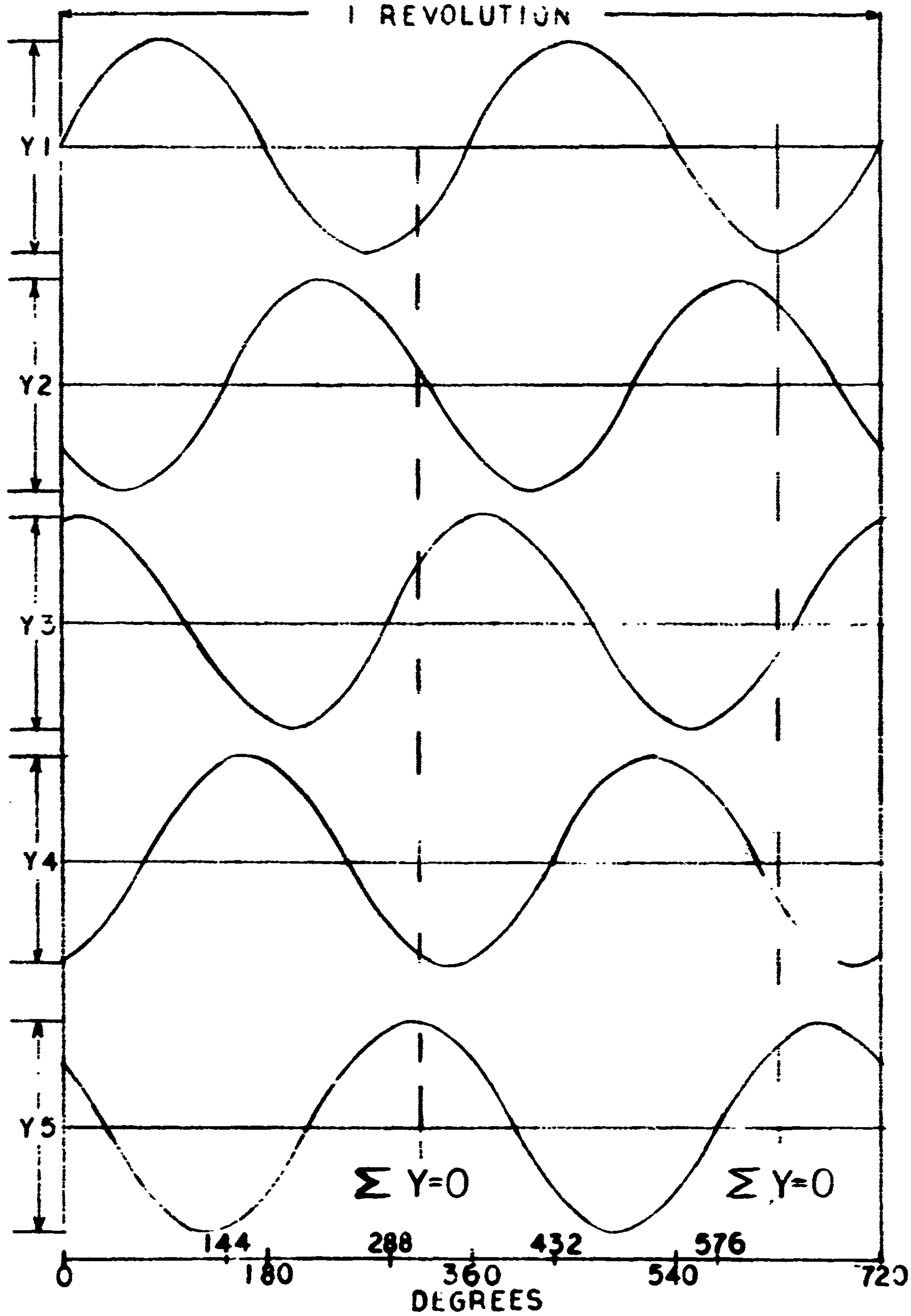

FIGURE 19. A C BLADE CURRENT - 2/REV

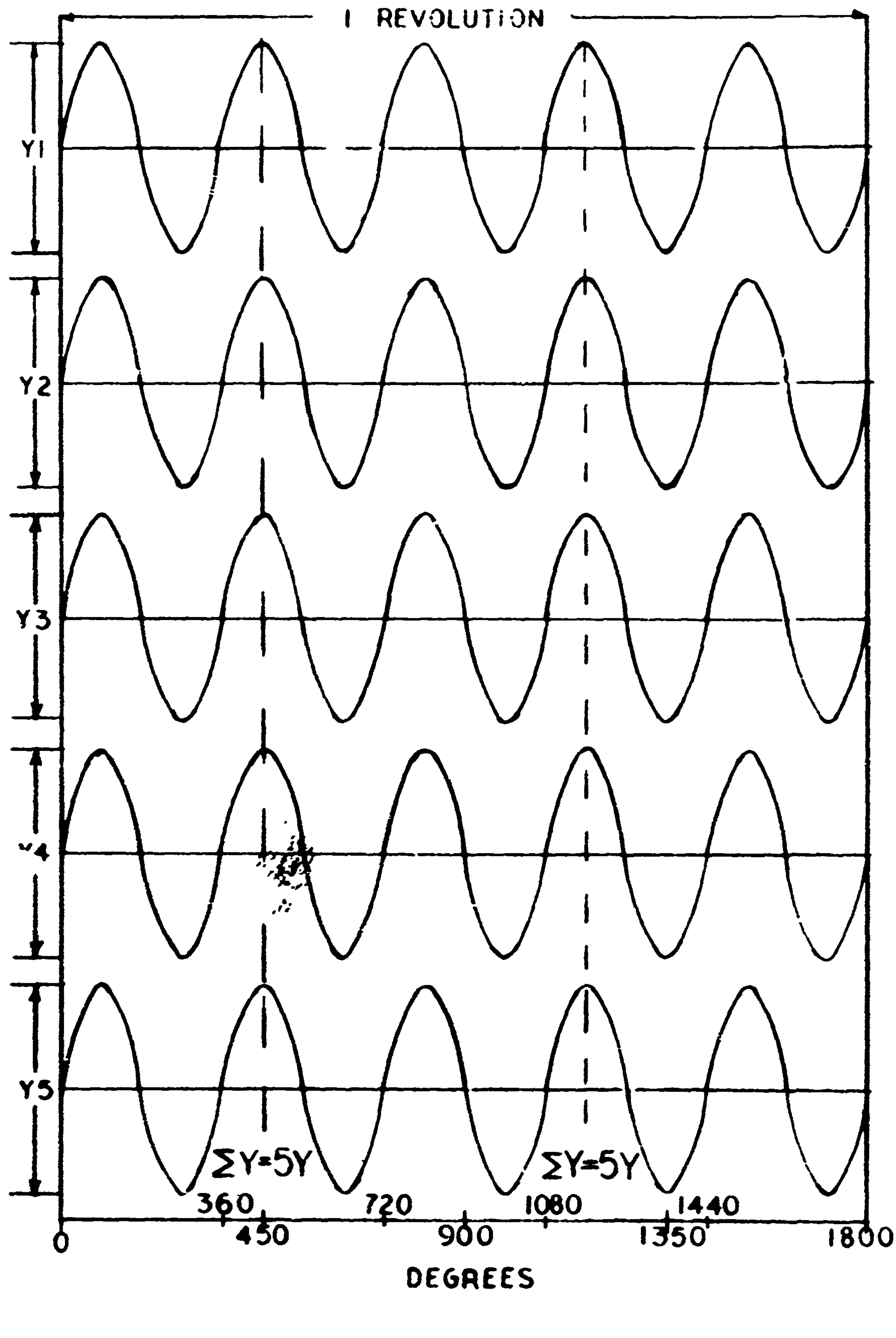

FIGURE 20. A C BLADE CURRENT - 5/REV

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U. S. Army Engineer Research and Development Laboratories	3
U. S. Army Signal Research and Development Laboratory	1
U. S. Army Signal Research and Development Laboratory Liaison Office	1
U. S. Army Limited War Laboratory	1
Army Research Office-Durham	2
U. S. Army Test and Evaluation Command	3
U. S. Army Research Support Group	1
U. S. Army Medical Research and Development Command	1
U. S. Army Combat Developments Command	1
U. S. Army Combat Developments Command Aviation Agency	2
U. S. Army Combat Developments Command Transportation Agency	2
U. S. Army Combat Developments Command Quartermaster Agency	1
U. S. Army Combat Developments Command Experimentation Center	1
U. S. Army War College	1
U. S. Army Command and General Staff College	1
U. S. Army Transportation School	1
U. S. Army Quartermaster School	1
U. S. Army Transportation Center and Fort Eustis	1
U. S. Army Infantry Center	2
U. S. Army Aviation Maintenance Center	1
U. S. Army Armor Board	1
U. S. Army Aviation Test Board	3
U. S. Army Arctic Test Center	3
U. S. Army Airborne, Electronics and Special Warfare Board	1
U. S. Army Aviation Test Activity	2
U. S. Army Transportation Engineering Agency	1

Air Force Systems Command, Andrews AFB	1
Air Force Systems Command, Wright-Patterson AFB	3
Air Force Flight Test Center, Edwards AFB	1
Air Proving Ground Center, Eglin AFB	1
Air University Library, Maxwell AFB	1
Chief of Naval Operations	1
Bureau of Naval Weapons	8
Bureau of Supplies and Accounts, N/D	1
U. S. Naval Postgraduate School	1
Naval Air Test Center	2
David Taylor Model Basin	1
Hq, U. S. Marine Corps	2
Marine Air Group 36	2
Marine Corps Educational Center	1
Marine Corps Liaison Officer, U. S. Army Transportation School	1
Hq, U. S. Coast Guard	1
Ames Research Center, NASA	1
NASA-LRC, Langley Station	1
Lewis Research Center, NASA	1
Manned Spacecraft Center, NASA	1
NASA Representative, Scientific and Technical Information Facility	2
Research Analysis Corporation	1
National Aviation Facilities Experimental Center	1
Human Resources Research Office	1
Defense Documentation Center	10
U. S. Government Printing Office	1